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HIGH TEMPERATURE STRESS-STRAIN ANALYSIS

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The objectives of the high-temperature structures program are threefold: to assist in the development of analytical tools needed to improve design analyses and procedures for the efficient and accurate prediction of the nonlinear structural response of hot-section components; to aid in the calibration, validation, and evaluation of the analytical tools by comparing predictions with experimental data; and to evaluate existing as well as advanced temperature and strain measurement instrumentation. As the analytical tools, test methods, tests, instrumentation, as well as data acquisition, management, and analysis methods are developed and evaluated, a proven, integrated analysis and experiment method will result in a more accurate prediction of the cyclic life of hot section components.

TEST FACILITIES

The two test facilities at Lewis which support the development of the analytical tools and the evaluation of advanced instrumentation are the high-temperature structures laboratory and the structural component response test facility. Both of these facilities have the capability to conduct controlled thermomechanical cyclic experiments under computer control. Small tubular specimens will be tested in the high-temperature structures laboratory (see fig. 1) using uniaxial and biaxial test machines. Larger specimens such as flat plates, cylinders, and combustor liner segments are tested in the structural component response test facility, which consists of two rigs that operate at atmospheric pressures. Flat-plate specimens (5 by 8 in.) are tested in the bench-top quartz lamp rig (see fig. 2); large, cylindrical (~20 in. diameter) and combustor liner specimens are tested in the annular quartz lamp rig (see fig. 3). The high-temperature structures laboratory should be operational by early 1986; the bench-top quartz lamp rig and the annular quartz lamp rig are operational.

High Temperature Laboratory

Two uniaxial test machines (load capacity, ±20-kip) and two biaxial test machines (±55-kip load in tension/compression and 25-kip in torsional capacity) are used in the high-temperature structures laboratory for deformation testing. Each of these machines is computer controlled by an S20 Data General computer. A larger Data General computer (MV/4000) is used for data storage, management, reduction, and analysis. Five-kilowatt-radiofrequency induction heaters are used with the uniaxial machines, and 50-kW-audiofrequency induction heaters will be used with the tension/torsion test machines. Instrumentation includes high-temperature water-cooled uniaxial extensometers for measuring strains on the uniaxial test machines. Two high-temperature biaxial extensometers will be tested and evaluated on the biaxial test machines. A third high-temperature biaxial extensometer will be evaluated as part of an interagency agreement with the Oak Ridge National Laboratory. High-temperature grips for the biaxial test machines have been fabricated.

Bench-Top Rig

The major components of the bench-top quartz lamp rig are shown in figure 2. Four quartz lamps (6 kVA) are used to heat the plate specimens. The lamps are air cooled, and the test fixture is water cooled. A manifold provides cooling air to the top surface of the test plate. The cooling air to the plate can be preheated to 400 °F. A lamp-out detection system determines when a lamp has burned out.

A dual-loop programmable controller, a microprocessor, is used to control the power to the lamps. A specified power-time history is programmed into the microprocessor, and the cooling air temperature and flow rate are appropriately set so that when combined, the desired thermal cycle is imposed on the test plate.

Thermocouples and an infrared thermovision system are used to obtain surface temperatures on the plate. There are provisions for taking 30 thermocouple measurements. A viewport, consisting of a 5-inch-diameter quartz window, provides access for obtaining an infrared thermal image. Both thermocouple and thermal image data are obtained on the cool side of the test plate. Only thermocouple data are obtained on the hot side (facing the four quartz lamps) of the test plate. The thermocouple data provide temperatures at discrete points, while the infrared system provides detailed maps of thermal information about the test specimen.

During a test run both the facilities data (pressures, flows, power, etc) and the research data (primarily temperature) are acquired for each thermal cycle using the ESCORT II data acquisition system at Lewis. These data can be stored automatically once every second on the Amdahl computer. The software, however, does allow for varying the time at which data are taken during a thermal cycle. These data can be displayed on CRT's in the control room with about a 4-sec delay time. To obtain real time readings of pertinent data, a strip chart recorder with nine channels is used.

The raw thermal images obtained from the infrared camera are stored on a VHS tape recorder, with the clock time superimposed on each image. Images of the test plate of from about 4 to about 1 in. in diameter (for finer resolution of temperatures) can be obtained with the zooming capability of the infrared system. Thirty thermal images are captured on tape every second. A computer system is then used to process, reduce, enhance, and analyze the transient temperature information. These data are also compared with the thermocouple data. Thermocouple data are used in the calibration of the infrared system.

Bench Top Rig Test Results

Some of the salient results of tests conducted on a Hastelloy-X flat plate, with dimensions of 8 by 5 by 0.05 in., are as follows: The plate temperatures are very repeatable from cycle to cycle. A 20-second ramp time from low to peak temperature on the plate was achieved. The nominal life of the quartz lamps is 500 thermal cycles. Actual lamp life, however, varies depending on power settings (maximum or minimum), the hold times at those settings, and the ramp rates for a given thermal cycle. The infrared thermovision system provides a qualitative measure (maps) and, in some cases, a quantitative measure of transient surface temperatures. The experience, data, and other information obtained from the bench-top rig tests have benefited the installation and checkout of the annular quartz lamp rig.

Annular Rig

Figure 3 shows the annular quartz lamp rig installation and its major components. This rig is being operated under a cooperative agreement with Pratt & Whitney Aircraft (PWA). G. Pfeifer of PWA is my coinvestigator on this project.

The quartz lamp heating system used to cyclically heat a test liner is shown in figure 4. One-hundred-twelve 6-kVA lamps configured circumferentially in 16 sectors, each having 7 lamps, are used to heat a 20-inch diameter test liner. This system, in addition to drawing up to 672 kVA of 480-V power, requires 3.5 lb/sec of ambient temperature air at 5 psig, 1.5 lb/sec of ambient temperature air at 1 psig, and 80 gal/min of specially treated water for cooling the rig.

A natural-gas and air mixture is burned in a combustor can upstream of the test section to provide preheated cooling air to the test liner. Cooling air temperatures of from 400 to 600 °F can be obtained by varying the fuel/air mixture ratio. The cooling airflow rate is variable from about 4.0 to 7.5 lb/sec at 35 psig. Both the cooling-air temperature and flow rate can be varied to obtain the desired cyclic temperatures on the test liner.

The annular rig has six 5-inch diameter viewports, three of which are spaced at 120° apart and are used to view the middle section of the test liner. The other three, also spaced at 120° apart, are used to view the upstream portion of the liner and its attachment piece. These windows are rotated 45° from the liner windows. The quartz windows are air and water cooled. Through these windows television cameras and the infrared camera are used to monitor and take temperature measurements on the liner. There are also provisions for having almost 100 thermocouples on the test liner.

The dual loop programmable controller system, the ESCORT II data acquisition system, and the infrared thermovision system, described previously for the bench-top rig application, are the same systems used for the annular rig.

For the checkout of the annular rig, a conventional combustor test liner (stacked-ring louver configuration supplied by PWA) was installed in the test section. Its purpose was to assist not only in the checkout of each of the rig systems, but also to identify potential test problems and possible integrated analysis/experimental complications and to provide some thermal cyclic data such as liner temperatures and distortions. These data were used in the preliminary structural analysis of the liner. Shown in figure 3 is the instrumented liner mode of Hastelloy-X material. Seventy thermocouples provided the temperatures: 55 were used to monitor the cool-side temperatures, and 15 monitored the hot-side temperatures.

Annular Rig Test Results

After the rig checkout steady-state and transient tests were conducted to determine the thermal response of the liner under various test conditions. Combinations of power settings, cooling airflow rates, cooling air temperatures, and ramp times were conducted. The results of these tests were used to determine the appropriate settings of the test control variables to obtain surface metal temperature profiles similar to those of an actual combustor liner. Other concerns that affected the settings of the test variables were lamp life, rig temperature, and rig durability.

Figure 5 shows the peak steady-state cool-side temperatures of the louver test liner as a function of power settings for a cooling airflow rate of 5.5 lb/sec and cooling air temperatures of 400, 500, and 600 °F. The two other cooling flow rates were 6.5 and 7.5 lb/sec. Plotted in figure 6 are the minimum temperatures for the same test conditions. The minimum and peak temperatures occur at different locations on the liner. Peak temperatures were taken from a thermocouple mounted on the louver weld. And minimum temperatures were taken from a thermocouple mounted on the louver knuckle. Over the power range plotted the peak temperatures differ by about 50° between the cooling air temperatures, whereas the minimum temperatures differ by about 100 °F.

From the steady-state data and ramp tests, not reported here, a power versus time curve was determined that simulated an actual engine mission thermal cycle. The power history for the thermal cycle is shown in figure 7. The cyclic test conditions were a coolant flow rate of 5.5 lb/sec, a coolant flow temperature of 600 °F, a minimum power of 38 percent (actual), and a maximum power of 83 percent (actual). The total thermal cycle time was 2.2 minutes. The time was broken up into a 6-sec ramp up time from minimum to maximum power, a 60-sec hold time at maximum power, a 6-sec ramp down time, and a 60-sec hold time at minimum power. This power history was programmed into the dual-loop programmable controller. The controller was run in the set-point control mode.

Figure 8 shows the temperature response to the power history of a thermocouple mounted on the hot side of the louver weld. For the 6-sec ramp up in power there was about a 25-sec time required for the liner temperature to reach equilibrium conditions, or about a 20-sec lag between the time to maximum power and stable peak liner temperatures. The 6-sec ram down-time results in an almost mirror image of the ramp up in terms of time for the liner to reach stable minimum temperatures. The ramp up and the ramp down times simulate the ascent and descent phases of an engine mission cycle, and the hold time represents cruise conditions, where the interaction of creep and plasticity occur simultaneously.

Some typical thermocouple data are shown in figures 9 and 10. The data shown are the cool-side temperatures at maximum power of the cluster of thermocouples for the 450th thermal cycle. These data are used to plot axial and circumferential temperatures for the fourth and fifth louver liners on the liner. Examples of these types of plots are shown in figures 11 and 12. These temperatures are used in the heat-transfer/structural analysis of the liner.

The infrared thermovision system is used to obtain a more detailed map of the cool-side liner temperatures. Figure 13 is an example of the IR data obtained. Plotted are axial temperatures on the louver No. 4. Only the temperatures are shown for the maximum and minimum powers at steady-state conditions of the thermal cycle. With this system over 10^7 temperature measurements are obtained for each thermal cycle. Thermocouple data are also shown for comparison.

The test liner was subjected to 930 heating cycles, including the initial parametric testing. For the bulk of the tests, the cycles produced a liner hot-side surface temperature at the highest-reading thermocouple of nominally 1815 °F at 83 percent power and 1140 °F at 38 percent power. Only a few of the thermocouples failed during the tests. Thermocouple data indicated that the surface temperatures were remarkably stable and repeatable over the hundred of cycles. Temperature variation at maximum power over the hundred of cycles was generally no more than ±25 °F. Inspection of the liner on several occasions showed minor distortion of several segment lips. The distortion was symmetric with the 16 quartz lamp zones.

Of the 112 original quartz lamps, 35 lamps were replaced. Criteria for lamp replacement were excessive darkening of the glass envelope or sagging filaments. The remaining original lamps (77 of 112) operated for 930 cycles and 52 hours, of which 23 hours were at 80 percent or greater power. Based on the cumulative failures to date, a statistical analysis predicts a lamp half life of 85 hours.

ANALYSIS

The liner surface temperature measurements obtained from the thermocouples and the infrared thermovision system were used first to obtain the film coefficients on the cool and hot surfaces and then to compare them with predictions. Figure 14 shows the values of the film coefficients for louver 4.

The heat-transfer analysis was performed using MARC, a general-purpose, nonlinear, finite-element heat-transfer and structural-analysis program. A two-dimensional, axisymmetric, transient, heat-transfer analysis of the louver was performed. Eight-node, heat-transfer finite elements were used in the analysis, and 107 elements and 522 nodes were used to model the louver. Figure 15 shows both predicted cool-side liner temperatures and the experimental data at maximum power (83 percent) obtained from the infrared thermovision system. The figure shows good agreement between prediction and experimental data at this power level, but at lower power levels the prediction is not quite as good. A temperature contour plot at the maximum power level is shown in figure 16. There is also good agreement between transient temperature predictions and experimental data.

The MARC program produces a tape which contains the temperature information. The temperatures (or thermal loads) are then input to the structural-analysis program. The MARC program was also used to perform the structural analysis. A two-dimensional axisymmetric transient structural analysis of the louver was performed. Eight-node-structure finite elements were used in the analysis. The stress model was identical to the heat-transfer model. Symmetric boundary conditions were assumed at the ends of the louver. Walker's viscoplastic constitutive model was used in the analysis. This viscoplastic model, and others like it, accounts for the interaction between creep and plasticity, strain rate effects, time-independent and time-dependent effects, and other effects critical to a combustor-liner analysis and design.

Figure 17 is a hysteretic plot of hoop stress versus hoop strain for a point very near the cool spot on the liner. Figure 18 is a hysteretic plot of hoop stress versus hoop strain, for a point near the weld. These data could be used to identify critical failure locations in a liner and provide for better damage or fatigue/failure predictions.

To date no strain (or displacement) measurements have been taken on a flat plate or a test liner. However, plans are underway to begin to evaluate advanced static strain measurement systems, on both contact and noncontact devices. High-temperature (1300 °F), temperature-compensating resistant strain gauges will be evaluated on tubular and flat-plate Hastelloy-X specimens. This is a cooperative effort with the Instrumentation group at Lewis. Proximity transducers will also be evaluated. In addition, a laser specklegram system developed by C. Stetson at United Technologies Research Center (UTRC) will be evaluated on the bench-top rig. This also is a cooperative effort with UTRC and the Instrumentation group at Lewis. It is these strain measurements that will be then used to validate and evaluate the structural analytical tools now being developed.

CONCLUSIONS

The high temperature structures laboratory should be operational by early 1986. The bench-top quartz lamp rig and the annular quartz lamp rig are operational. Some preliminary tests have been conducted in both of the quartz lamp rigs. Over 900 thermal cycles were accumulated on a conventional sheet-metal louver combustor liner in the annular rig. Liner temperatures were stable and repeatable not only for each thermal cycle but from test to test. The temperature data obtained from thermocouples and the infrared camera are being analyzed and used in a preliminary heat-transfer analysis of the liner. Preliminary nonlinear, structural analyses are also being performed using as input the thermal loads obtained from the thermal analyses.

FUTURE RESEARCH

A second conventional sheet metal louver combustor liner is being instrumented with 105 thermocouples. Testing of this liner in the annular rig should begin by early November. Plans are also to test straight cylindrical specimens. An advanced liner is scheduled to be tested in early 1986. Advanced, high-temperature strain gauges and a laser specklegram system are to be evaluated on the bench-top rig in early 1986.

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HIGH-TEMPERATURE FATIGUE AND STRUCTURES LABORATORY

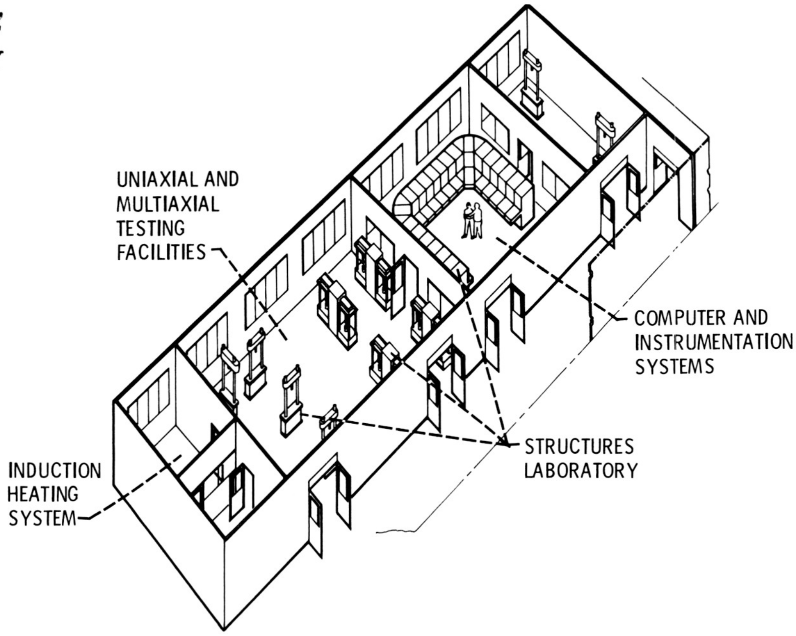

Figure 1

BENCH-TOP QUARTZ LAMP RIG

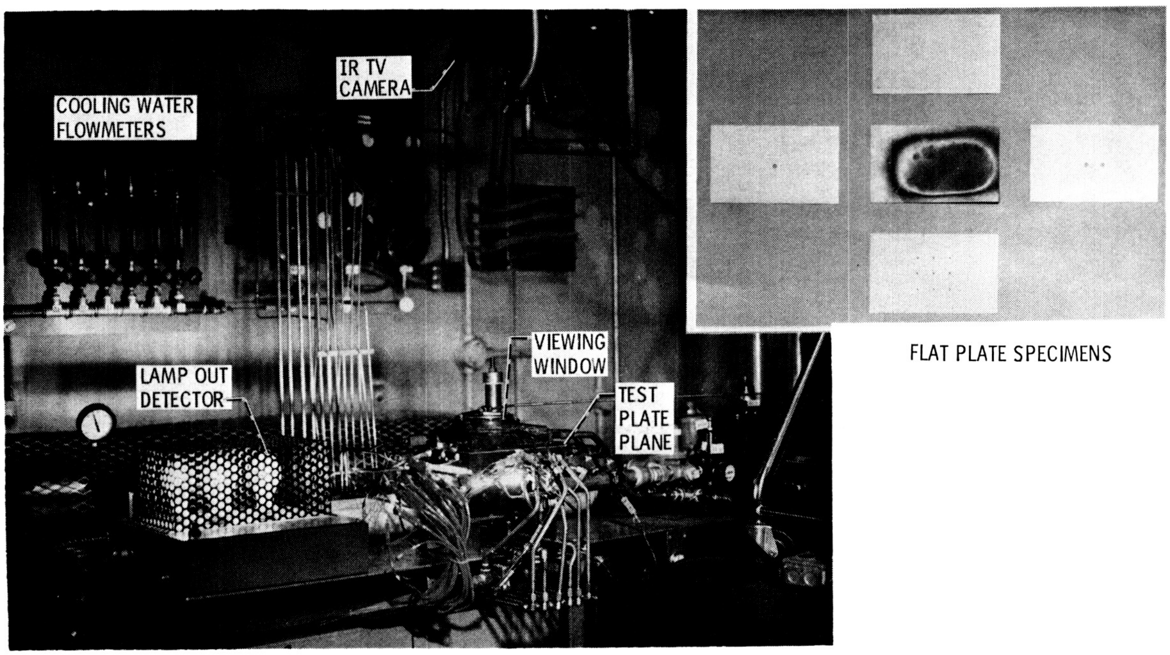

Figure 2

ANNULAR QUARTZ LAMP RIG

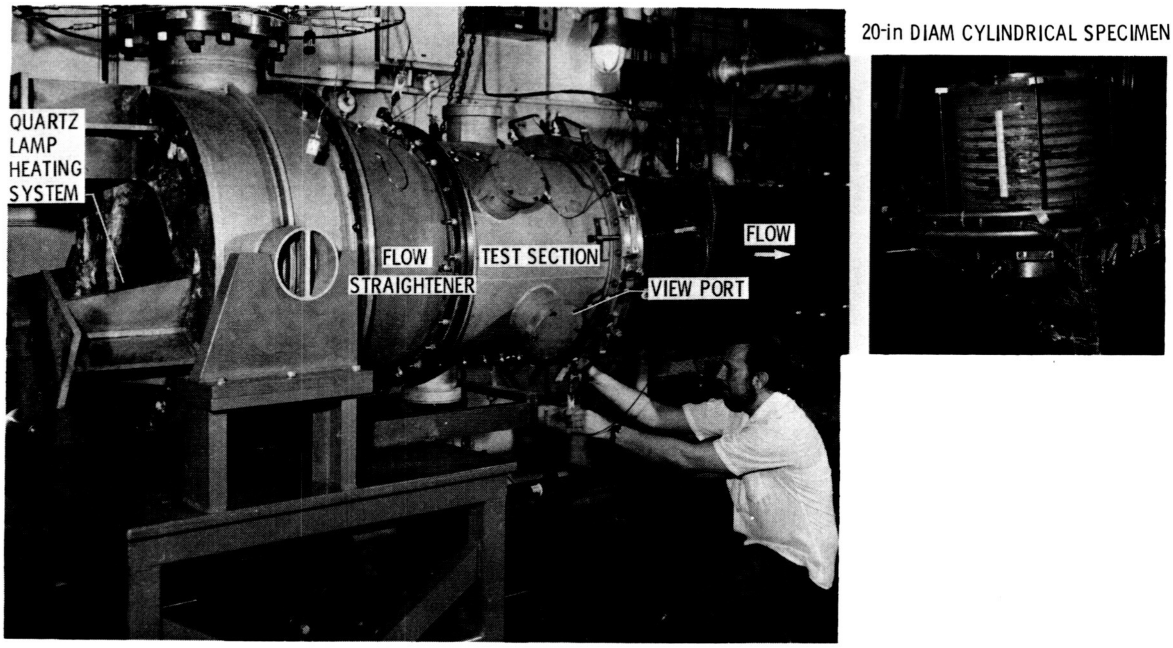

Figure 3

QUARTZ LAMP HEATING SYSTEM

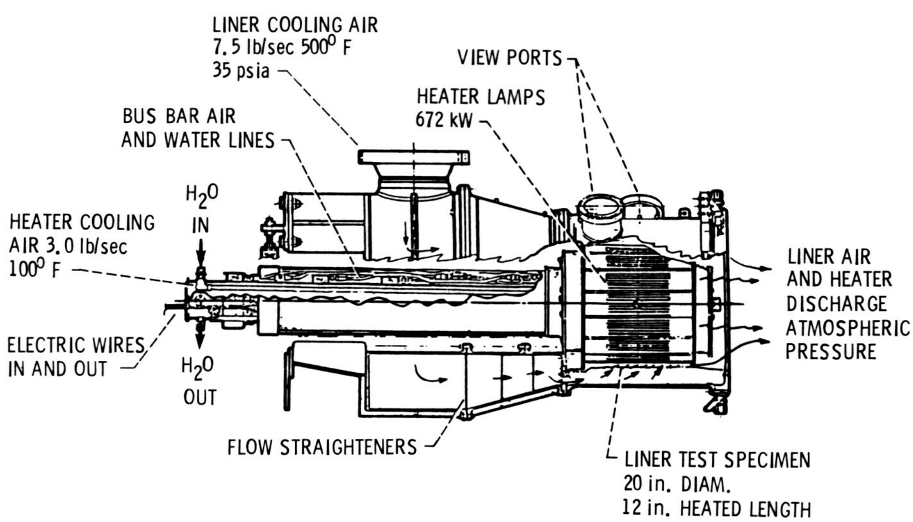

Figure 4

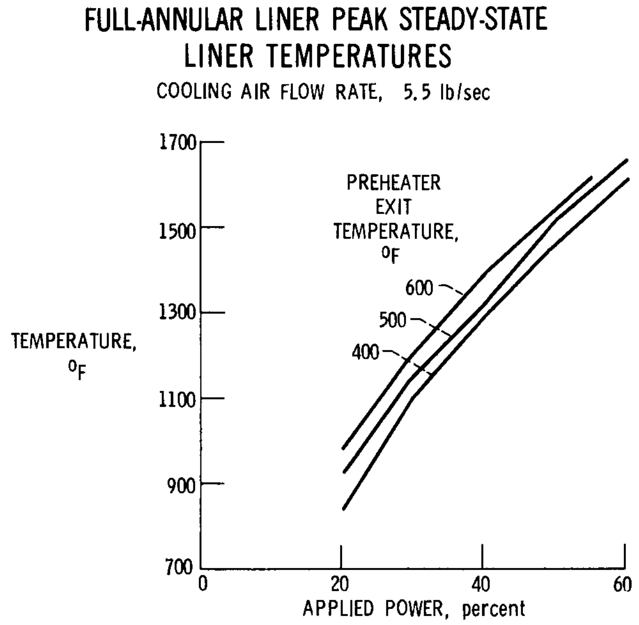

Figure 5

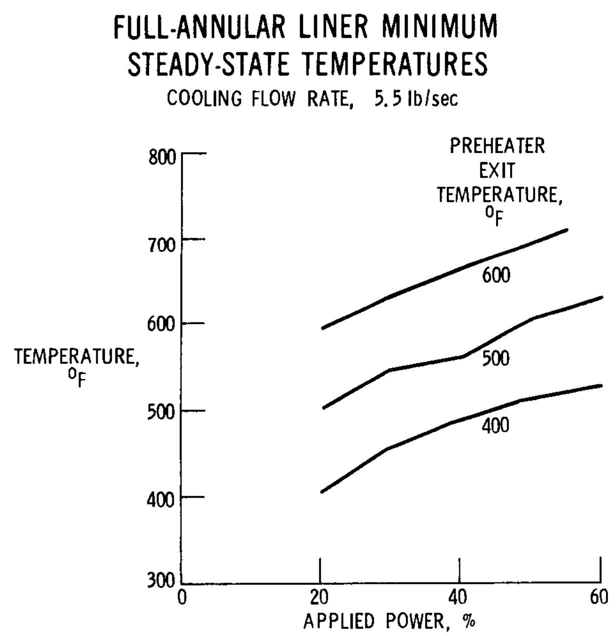

Figure 6

POWER HISTORY FOR THERMAL CYCLE

COOLANT FLOW RATE, 5.5/sec; COOLANT FLOW TEMPERATURE, 600 °F

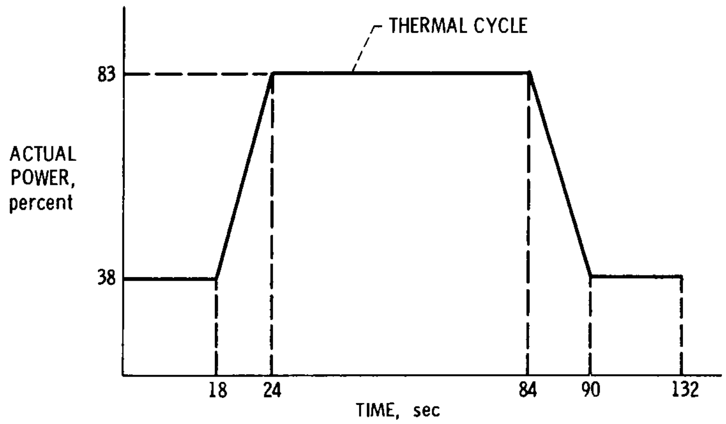

Figure 7

MEASURED PEAK COMBUSTOR LINER TEMPERATURE

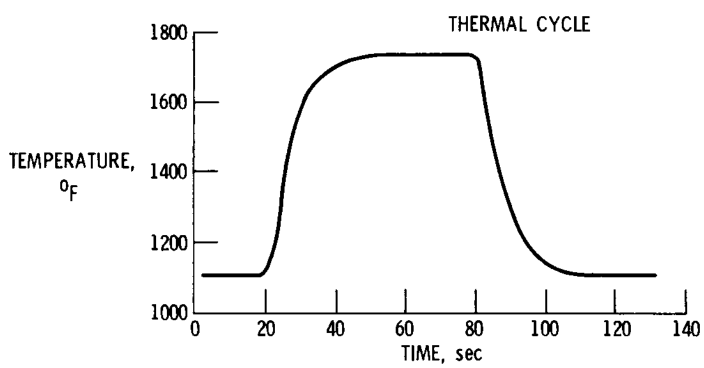

Figure 8

TYPICAL COOL-SIDE TEMPERATURES AT MAXIMUM POWER

450 THERMAL CYCLES

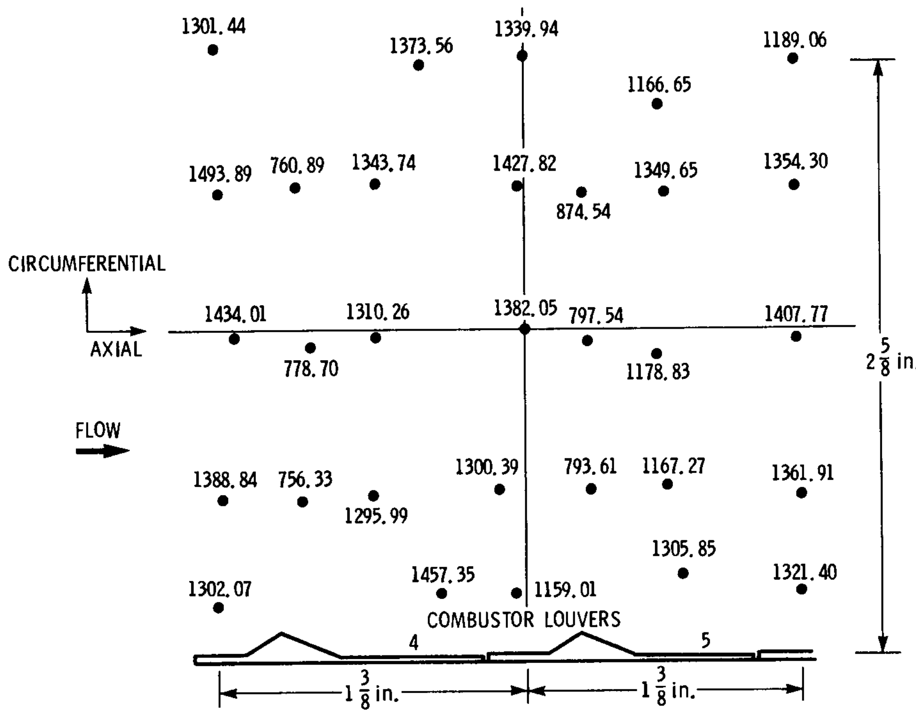

Figure 9

TYPICAL COOL-SIDE TEMPERATURES AT MINIMUM POWER

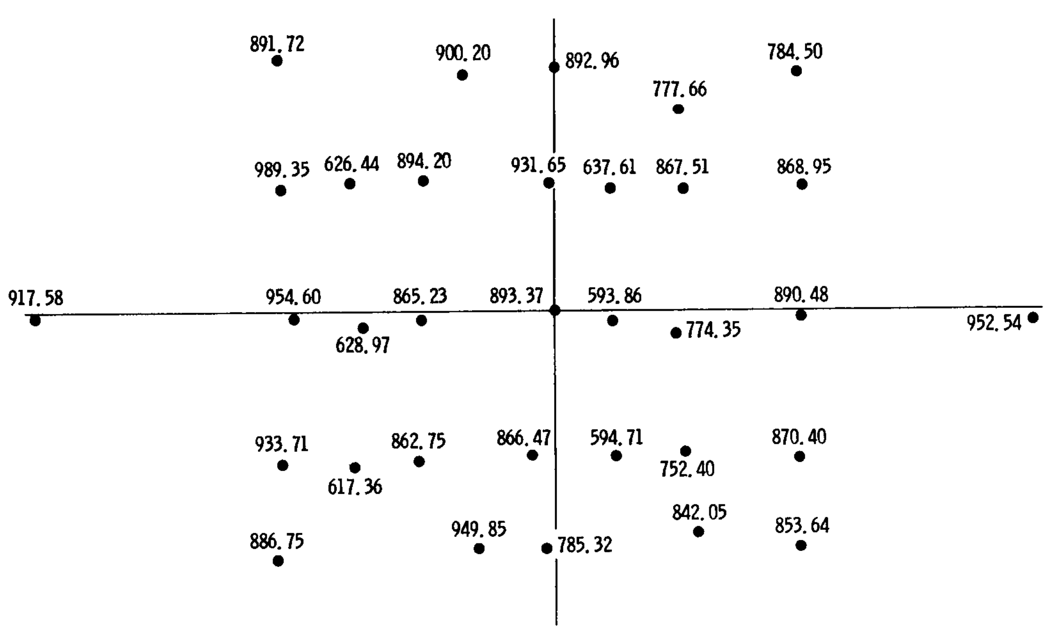

Figure 10

AXIAL COOL-SIDE LINER TEMPERATURES AT MAXIMUM POWER

FOR THREE AXIAL LOCATIONS THERMOCOUPLE

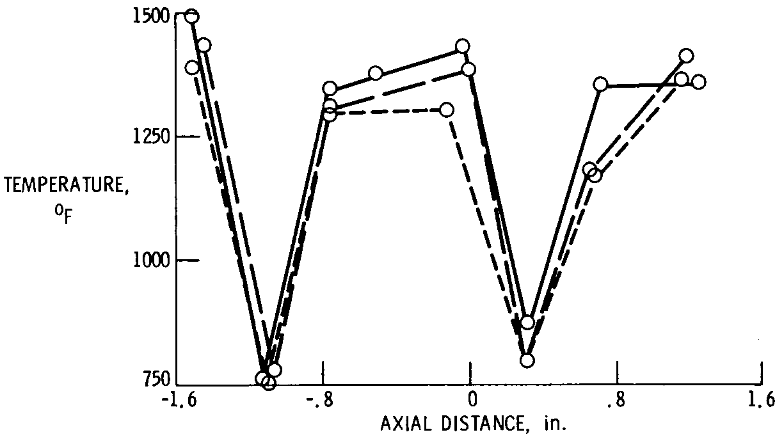

Figure 11

CIRCUMFERENTIAL COOL-SIDE LINER TEMPERATURES AT MAXIMUM POWER

FOR THREE CIRCUMFERENTIAL THERMOCOUPLE LOCATIONS

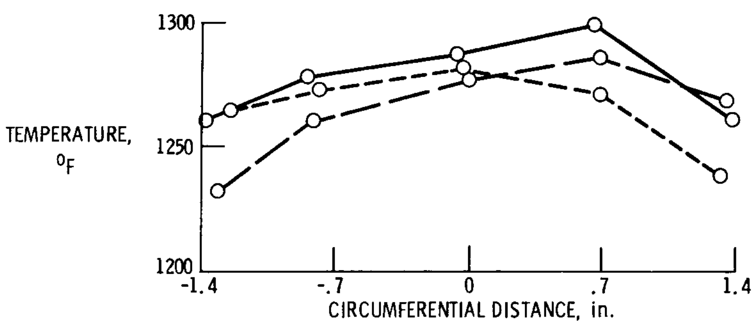

Figure 12

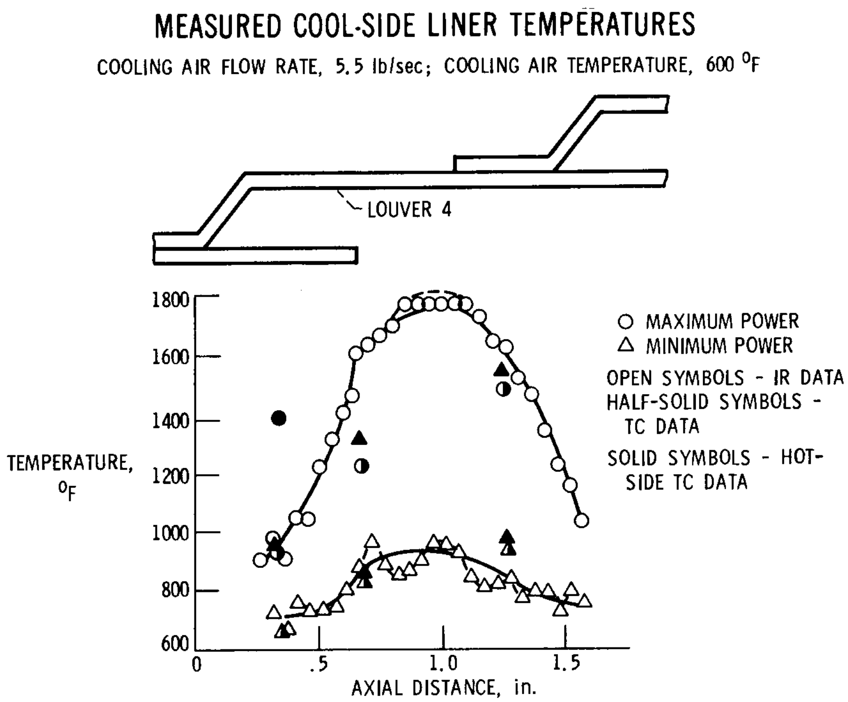

Figure 13

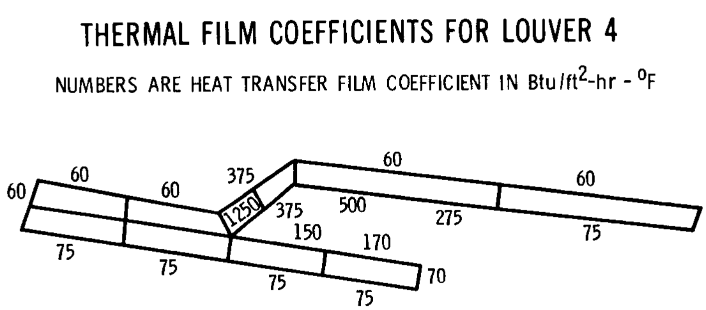

Figure 14

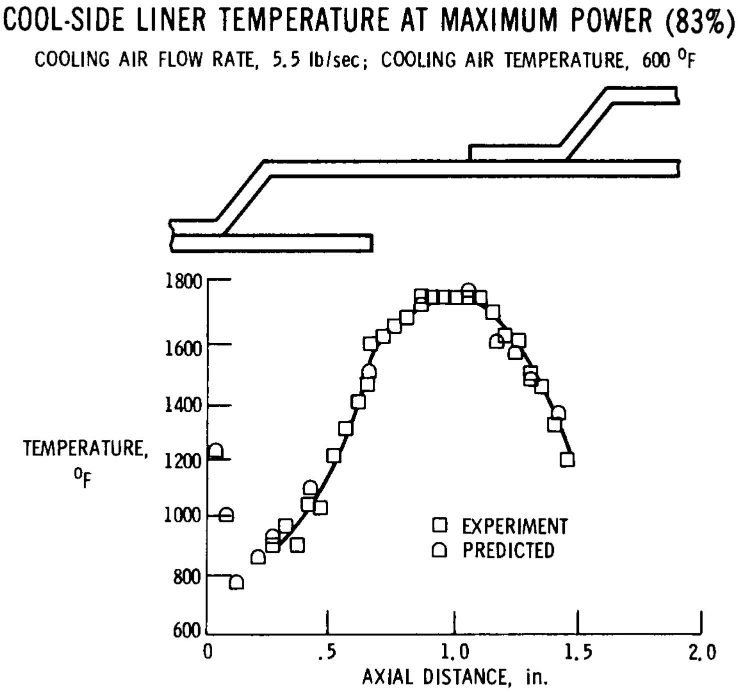

Figure 15

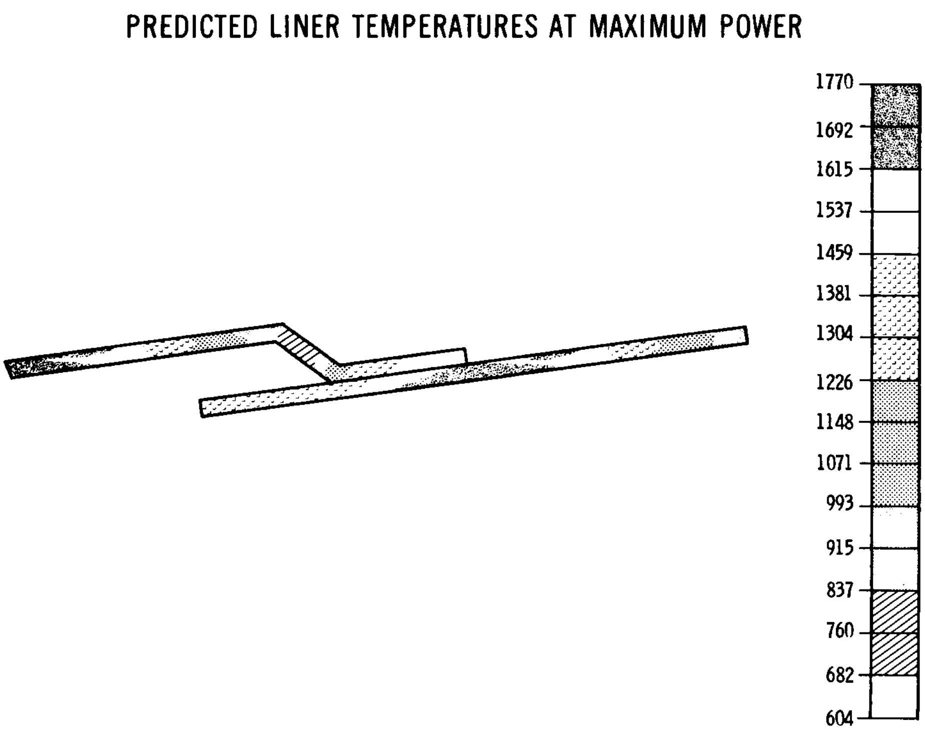

Figure 16

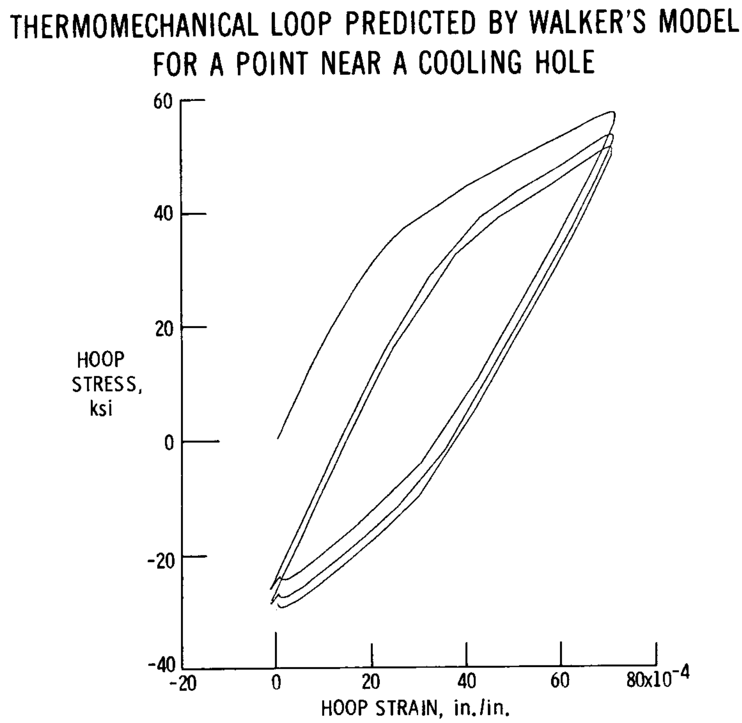

Figure 17

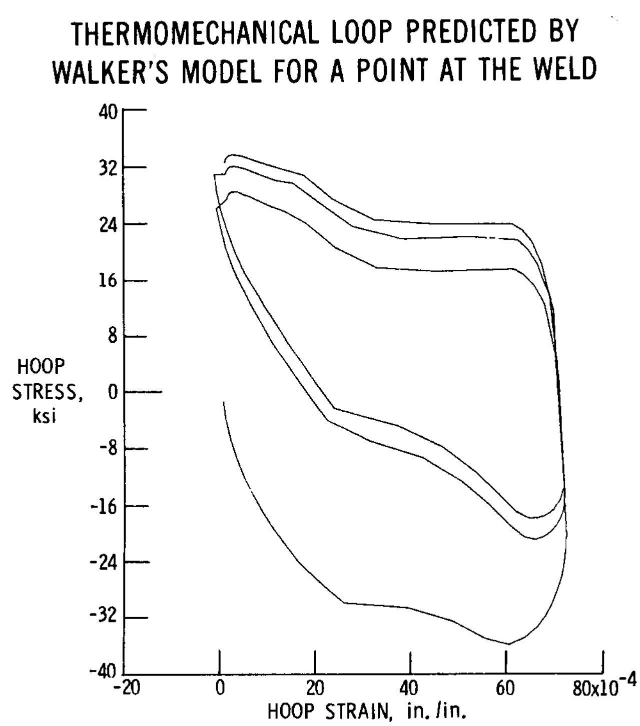

Figure 18